

P3 The Role of Reactant Unmixedness, Strain Rate, and Length Scale on Premixed Combustor Performance

S. Samuelsen (gss@uci.edu; 714-824-5468)
J. LaRue (jlarue@uci.edu; 714-824-6724)
S. Vilayanur (srv@uci.eng.uci.edu; 714-824-5950)
D. Guillaume (dguillau@uci.edu; 714-824-4995)
University of California, Irvine
UCI Combustion Laboratory
Irvine, CA 92697-3550

Abstract

Premixed natural gas fired combustors have the potential to significantly reduce NO_x emission for utility applications. The relationship between the inlet flow properties (e.g., turbulent length scales and intensity, temporal and spatial unmixedness, and anisotropy and mean strain rate) and the combustor performance (e.g., emissions, efficiency, stability, acoustics) is not well understood. The UCI program addresses this question using premixers amenable to parametric variation, in conjunction with a research combustor operated at atmospheric and practical pressures. Specifically, the program goals are to:

- Establish the relationship of inlet conditions to combustor performance (i.e., emissions, efficiency, stability, and acoustics).
- Determine the optimal levels of conditions to maximize combustor performance.
- Identify efficient premixing methods for achieving the necessary inlet conditions.

Emphasis is placed on minimizing pollutant formation without sacrificing efficiency. At the same time the combustor is required to have a large stability margin. The program involves broad interaction with industry in order to incorporate the needs and concerns of the relevant gas turbine groups into the design of the research combustor, the measurement protocol, and the results.

During the current reporting period, UCI has integrated the combustor with the controllable premixer, operated the system through extensive tests using design of experiments methods, and evaluated the results using a CFD code. Different cases of temporal and spatially inlet unmixedness are generated and repeated with the premixer. The degree of unmixedness is quantified and related to the combustor performance. The results and trends from the CFD package (FLUENT) correlate favorably to the experimentally established dependence of combustor performance to the inlet conditions.

In particular, combustor tests have been performed at conditions representative of industrial combustors (i.e., at 670K inlet preheat and at an equivalence ratio of 0.47). A custom designed fuel injector allows for variable inlet injection length, and three distinct modes of fuel injection.

This in turn 1) controls the presentation of fuel/air unmixedness into the combustor and 2) impacts the fuel temporal and spatial distribution. Swirl parameter variation is achieved via eight distinct swirlers. The swirler design is based on actual swirlers used in industrial. The combination of swirler and premixer configurations allow for a wide range of variability, that affects the combustion process.

In addition to spatial and temporal unmixedness, the swirl angle, swirl vane thickness and swirl solidity are also systematically investigated. Continuous monitoring of emissions are obtained at the exit of the combustor. Stability is investigated through the acoustic signature of the combustor.

The design of experiments approach is found to be a statistically effective tool by which effects can be identified and targeted for optimization. Early results suggest that the principal statistically significant effect on NO_x production is the inlet spatial distribution of fuel, and CO production is related to turbulent inlet properties (yet to be determined) that are influenced by swirl solidity.

In all the testing, the geometric characteristics of the swirl vanes have a strong effect on inlet conditions. This has spawned a directed study of swirl vane effects that includes unmixedness studies for a set of flat vanes. Correlations are obtained to determine the effect of vanes on the downstream flowfield. Vortices shed in a synchronized manner have been shown as a pathway to combustion instability. Studies have also revealed transitionally "flopping" modes that might be active in the combustion process. It is observed that the introduction of more vanes tends to suppress flow separation off the vanes. The unmixedness at locations before and after the swirlers used in the combustor tests are being obtained and will be compared to combustor performance results.

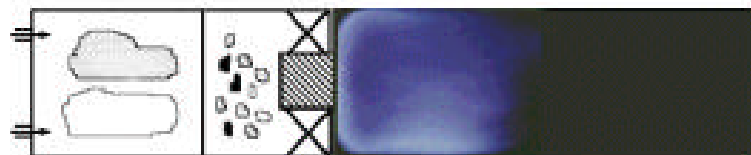
The direction of the program during the next reporting period is to target specific cases for detailed analysis and for high pressure applications. Diagnostic techniques will be incorporated along with numerical modeling to reveal the mechanistic processes that effect mixing and combustor performance. Continued industrial collaboration (Westinghouse, GE, Allison and Solar), will provide for technical exchange, and prove to be invaluable for both academia and industry.

Acknowledgments

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THE ROLE OF REACTANT UNMIXEDNESS, STRAIN RATE AND LENGTH SCALE ON COMBUSTOR PERFORMANCE

Scott Samuelson, Principal Investigator;
John C. LaRue, Co-investigator;
Suresh Vilayanur, Darrell Guillaume, Student Researchers



UCI Combustion Laboratory
University of California
Irvine, CA 92697

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South Carolina Energy Research and Development Center
Clemson, South Carolina 29634-5181

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Los Angeles, California 90051

- PREMIXING OF NATURAL GAS AND AIR IS THE STRATEGY BEING EMPLOYED TO REDUCE NO_x EMISSIONS.
- PREMIXING REQUIRES A FINITE LENGTH OF HARDWARE WHICH ADDS UNDESIRABLE VOLUME AND WEIGHT TO THE SYSTEM. IN ADDITION, SAFETY IS PLACED AT RISK DUE TO THE OPPORTUNITY FOR AUTO-IGNITION AND/OR FLASHBACK.
- LITTLE INFORMATION IS AVAILABLE THAT RELATES INLET CONDITIONS (UNMIXEDNESS, TURBULENCE PROPERTIES) TO COMBUSTION PERFORMANCE IN GAS TURBINE SYSTEMS.
- THE PRESENT PROGRAM ADDRESSES THE FOLLOWING QUESTIONS:
 1. WHAT IS THE EFFECT OF UNMIXEDNESS OF COMBUSTION PERFORMANCE?
 2. TO WHAT EXTENT DO THE INLET TURBULENCE PROPERTIES AFFECT COMBUSTOR PERFORMANCE?
 3. TO WHAT EXTENT CAN UNMIXEDNESS BE ACCEPTED WITHOUT COMPROMISING PERFORMANCE?
 4. WHAT IS THE MINIMUM DISTANCE REQUIRED TO ACHIEVE THE MINIMUM LEVEL OF FUEL/AIR MIXEDNESS?

- 1) DEVELOPMENT OF AN APPARATUS FOR THE CONTROL OF INLET LENGTH SCALE, MEAN STRAIN RATE, TURBULENT INTENSITY, AND UNMIXEDNESS
- 2) DETERMINATION OF THE EFFECT OF LENGTH SCALE, MEAN STRAIN RATE, TURBULENT INTENSITY ON UNMIXEDNESS
EVALUATION OF THE EFFECT OF SWIRL VANES (SOLIDITY, ANGLE, AND NUMBER OF VANES) ON LENGTH SCALE, MEAN STRAIN RATE, TURBULENT INTENSITY, AND UNMIXEDNESS
- 3) CHARACTERIZATION OF MODEL COMBUSTOR PERFORMANCE
- 4) MEASUREMENT OF THE EFFECT OF LENGTH SCALE, MEAN STRAIN RATE, TURBULENT INTENSITY, AND UNMIXEDNESS ON COMBUSTOR EMISSIONS AND PERFORMANCE

INLET

PERFORMANCE

PREMIXER

UNMIXEDNESS:
SPATIAL
TEMPORAL

SWIRL VANES

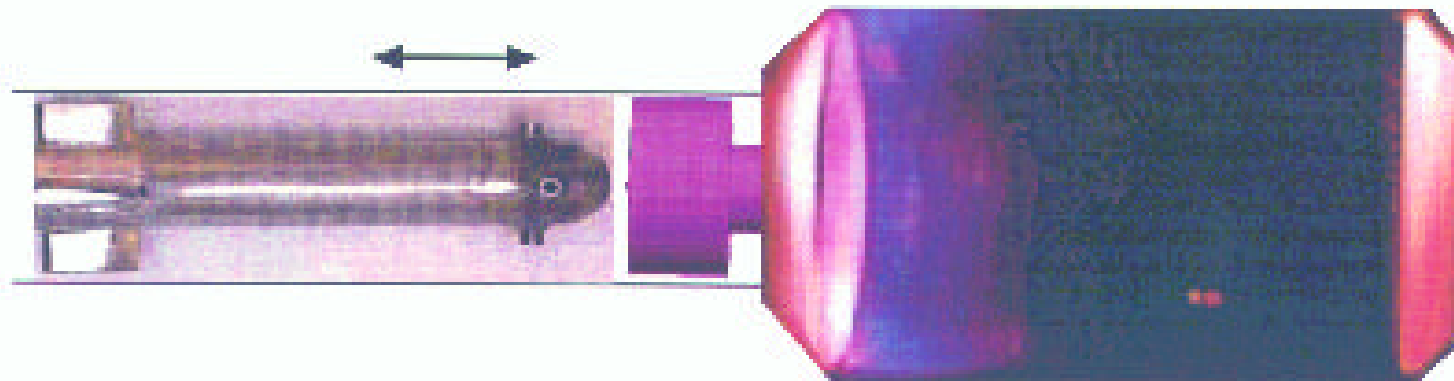
VANE THICKNESS
NUMBER OF VANES
VANE ANGLE

POLLUTANTS

EFFICIENCY

STABILITY

LEAN BLOWOUT

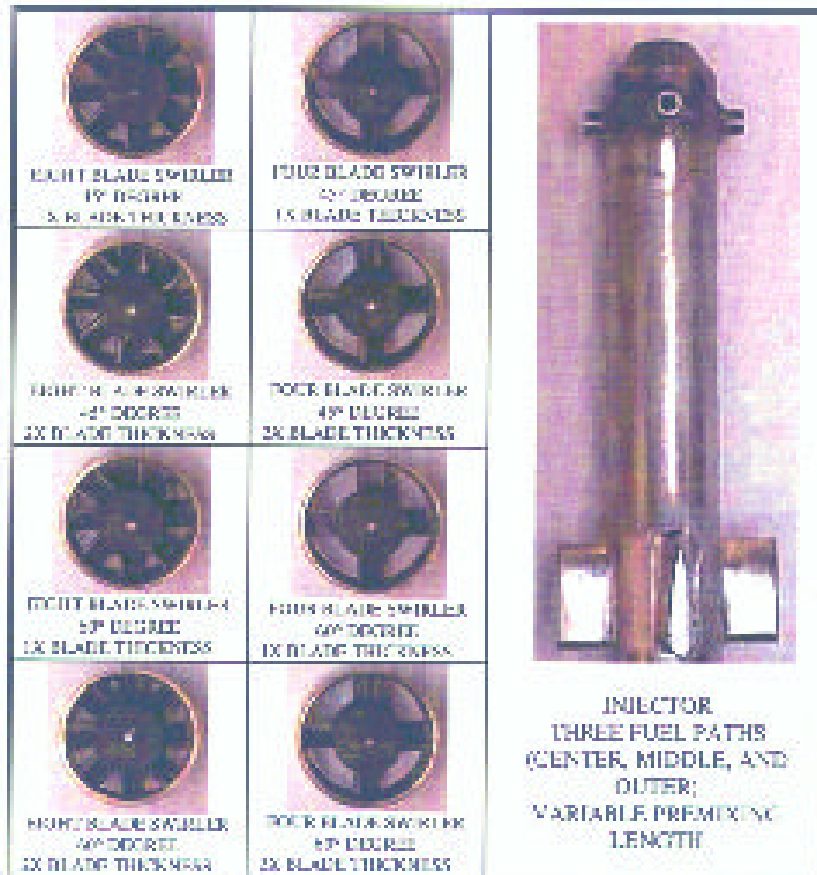


DESIGN OF EXPERIMENTS

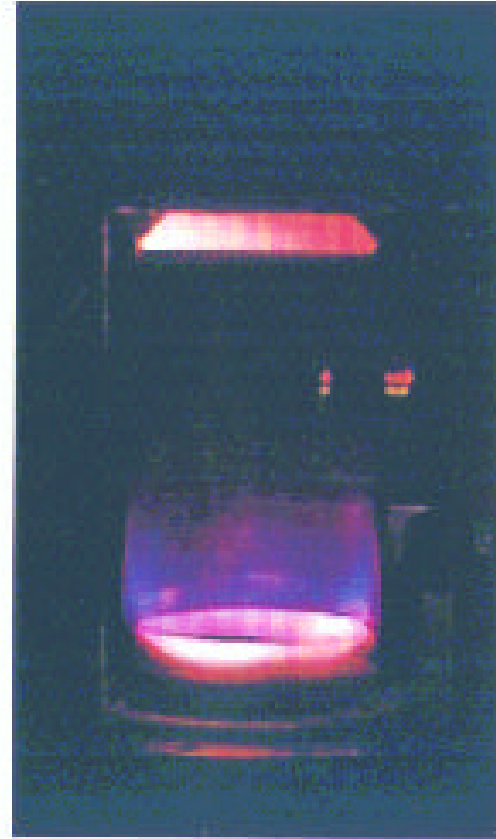
- STATISTICAL APPROACH
- ALLOWS FOR QUICK PARAMETRIC EVALUATION
- IDENTIFIES CRITICAL PARAMETERS
- IDENTIFIES INTERACTIONS BETWEEN PARAMETERS
- PROVIDES INFORMATION ON OPTIMAL SETTINGS

INLET HARDWARE

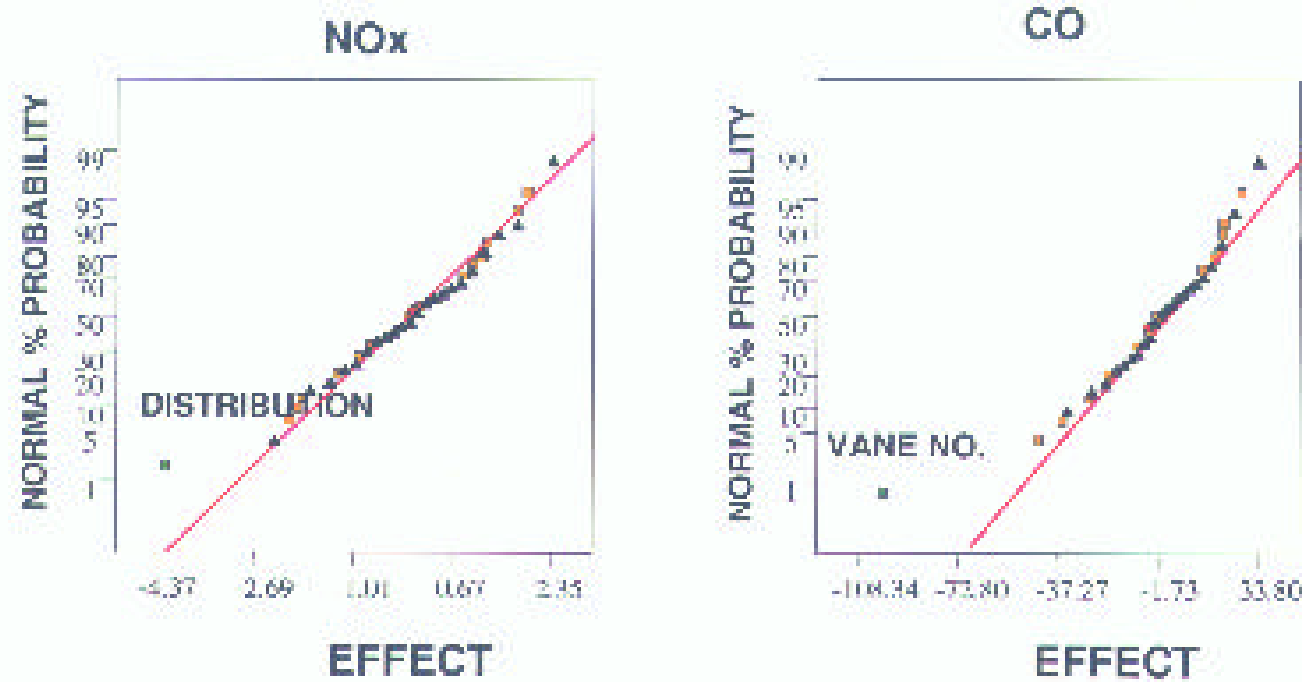
SWIRLER



- SWIRL ANGLE
- SWIRL THICKNESS
- SWIRL SOLIDITY
- FUEL DISTRIBUTION
- INJECTION LENGTH

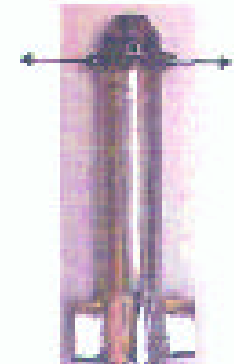
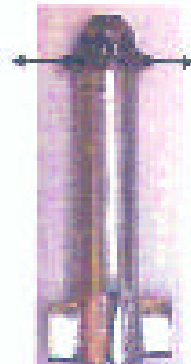
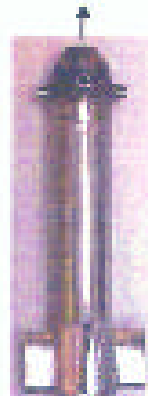
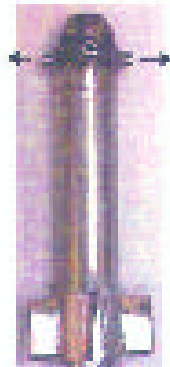
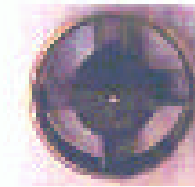
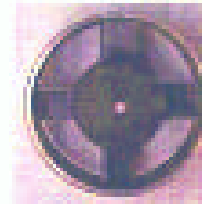
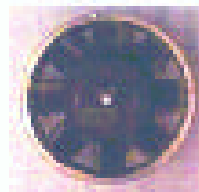


EFFECT PLOTS



- SWIRL ANGLE
- FUEL DISTRIBUTION
- SWIRL THICKNESS
- INJECTION LENGTH
- SWIRL SOLIDITY

UNMIXEDNESS-EXPERIMENT



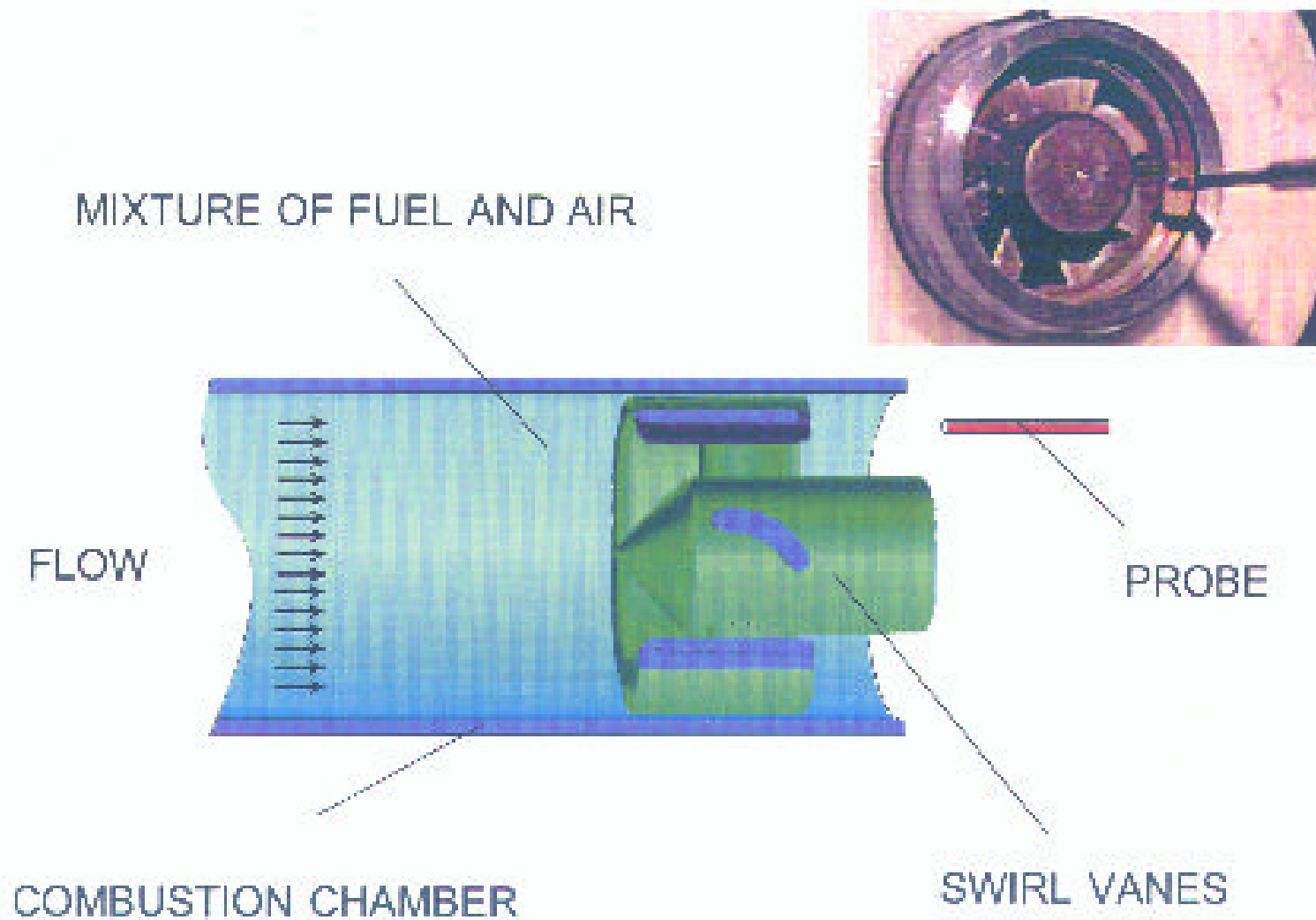
CASE 1

CASE 2

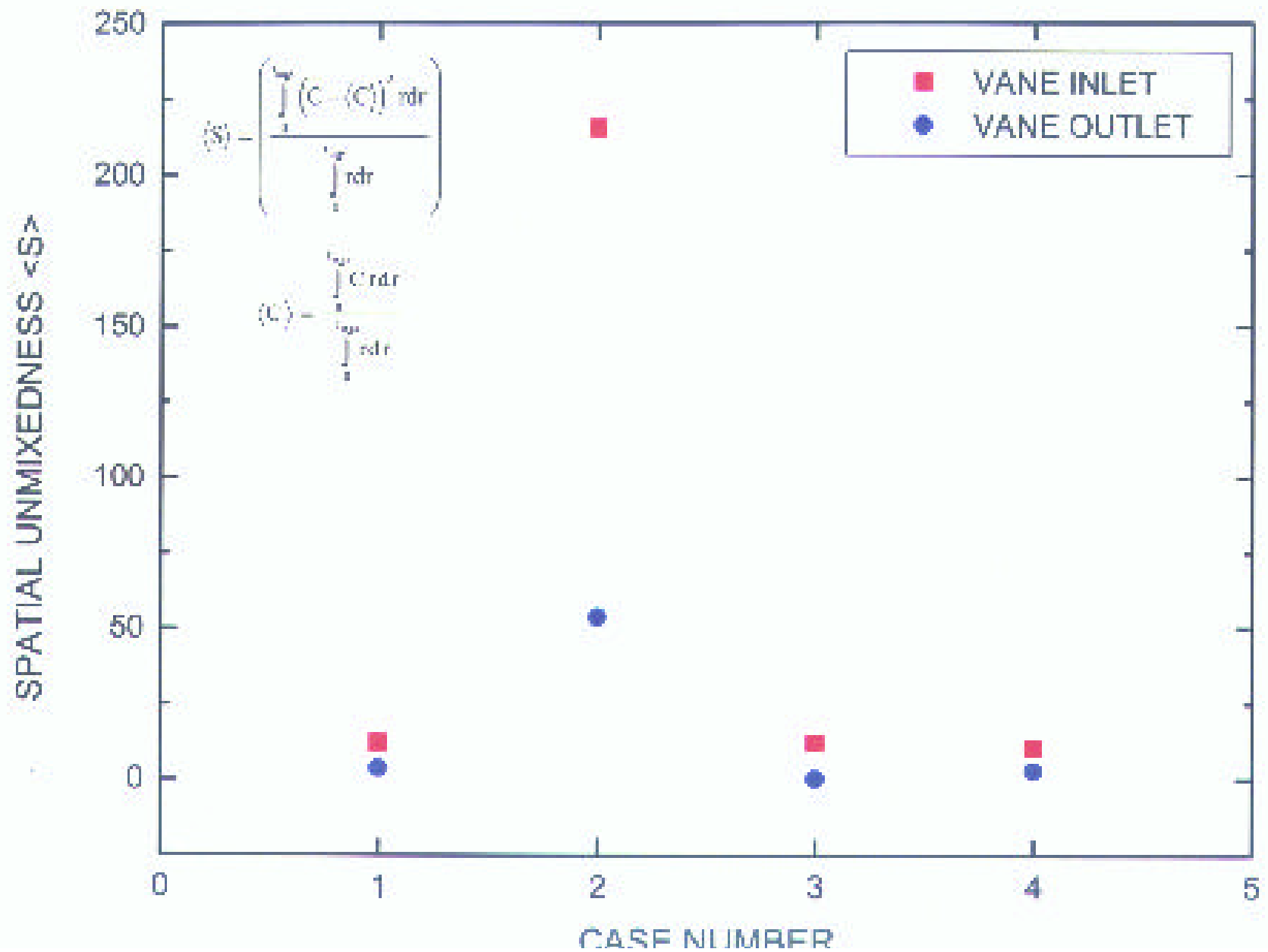
CASE 3

CASE 4

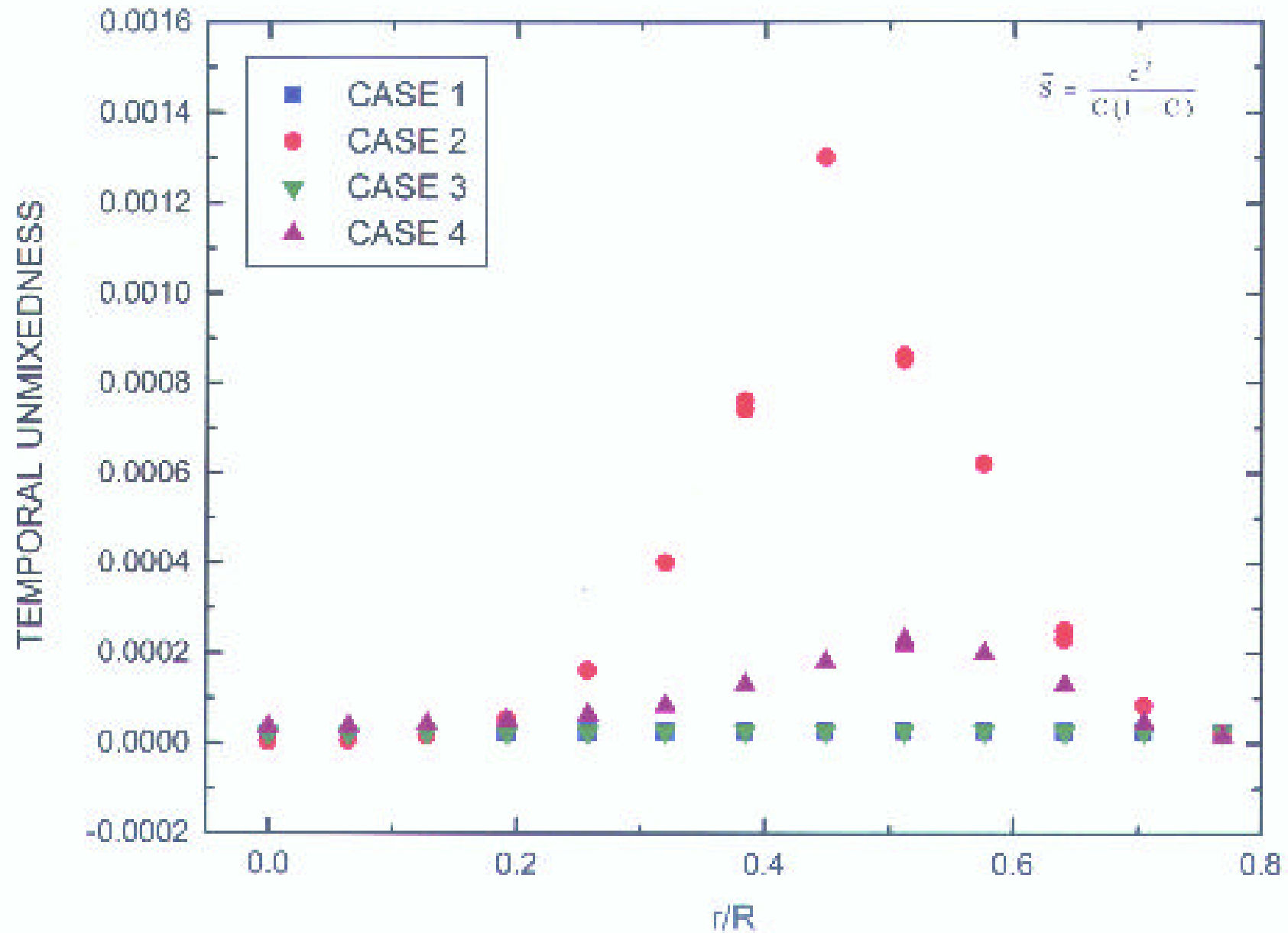
EXPERIMENTAL SETUP



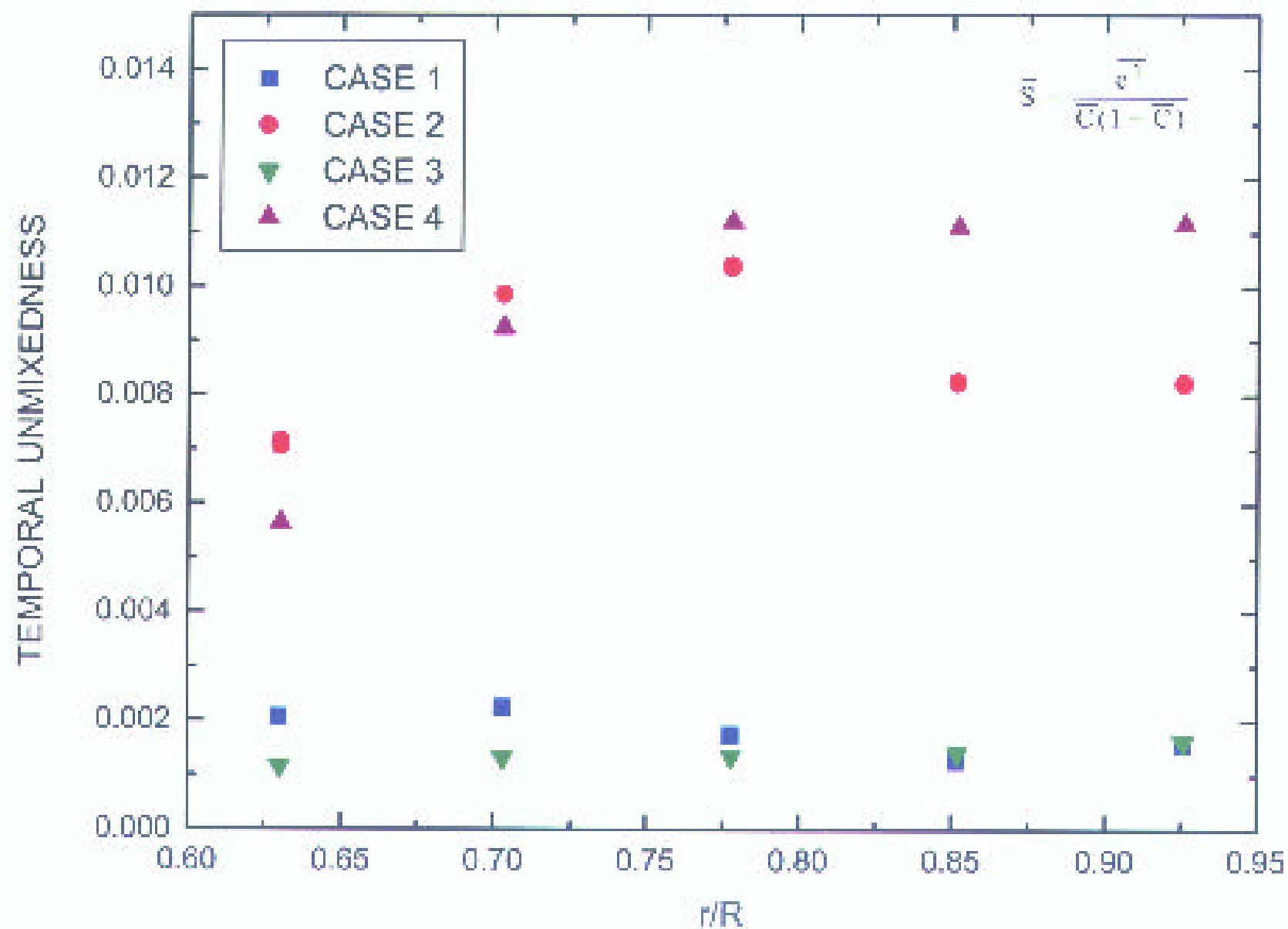
MEASURED SPATIAL UNMIXEDNESS



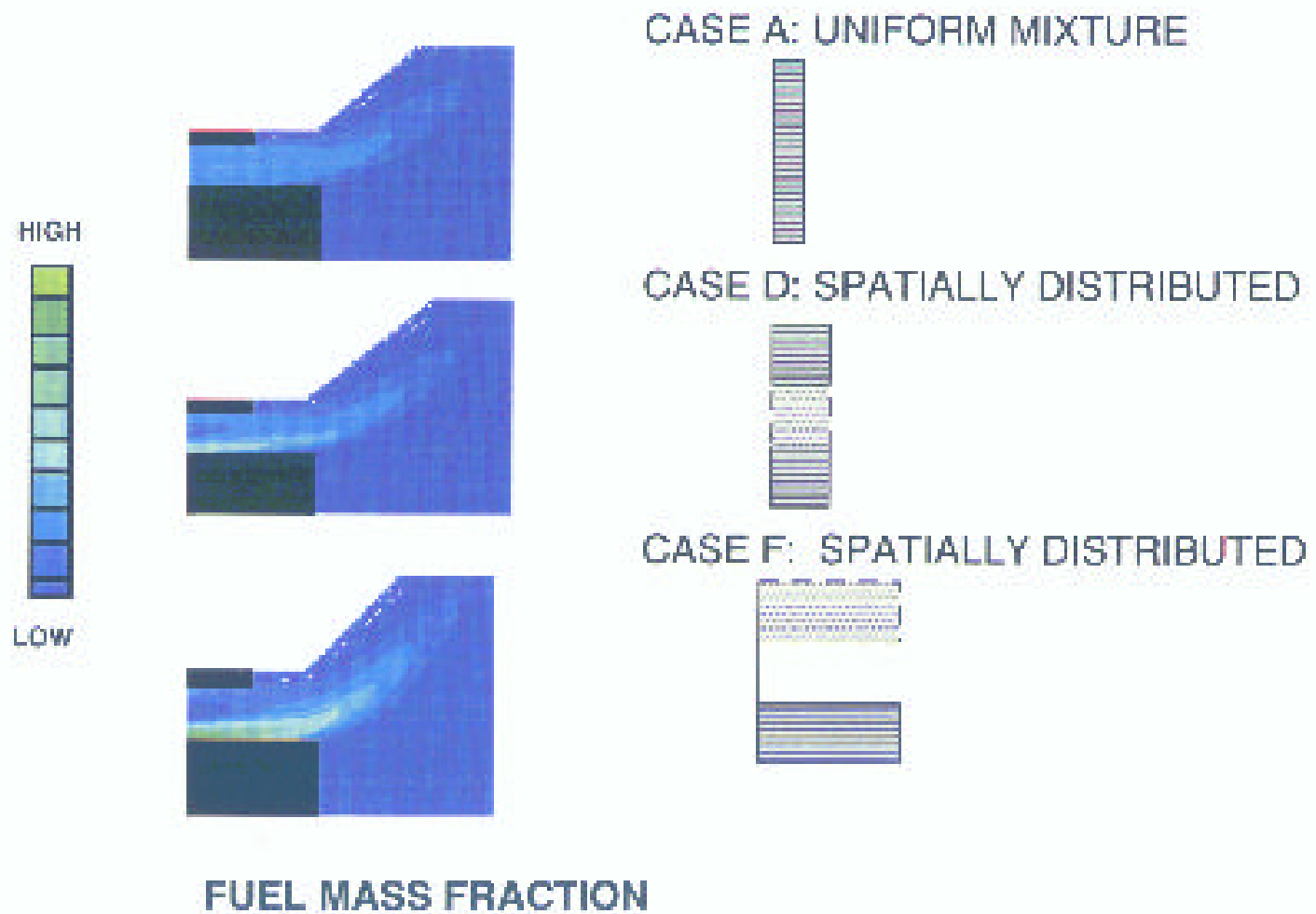
MEASURED TEMPORAL UNMIXEDNESS AT VANE INLET



MEASURED TEMPORAL UNMIXEDNESS AT VANE OUTLET

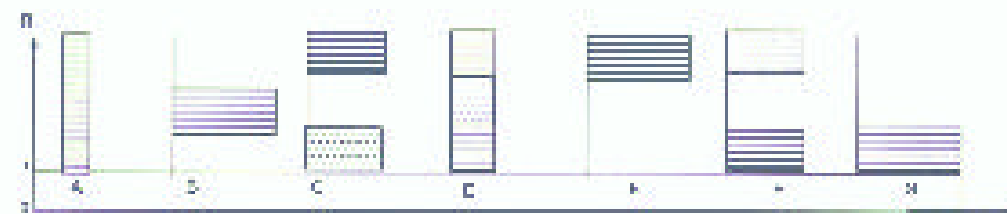


UNMIXEDNESS-CFD

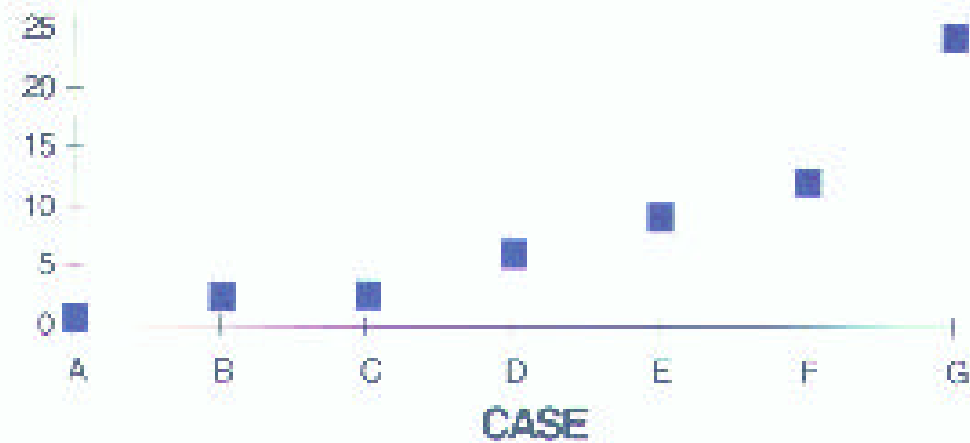


NO_x PREDICTION-CFD

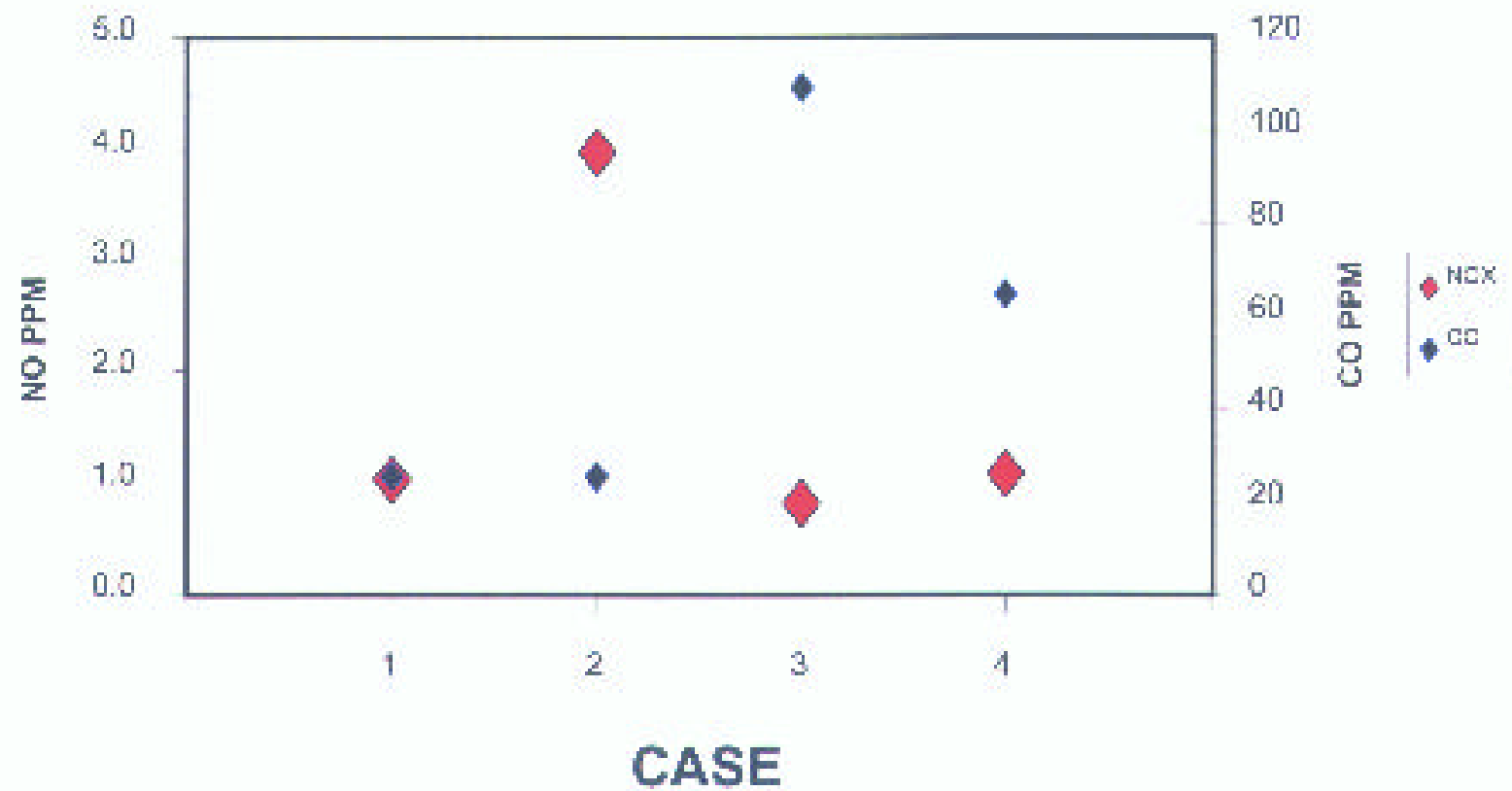
INLET
FUEL
PROFILES



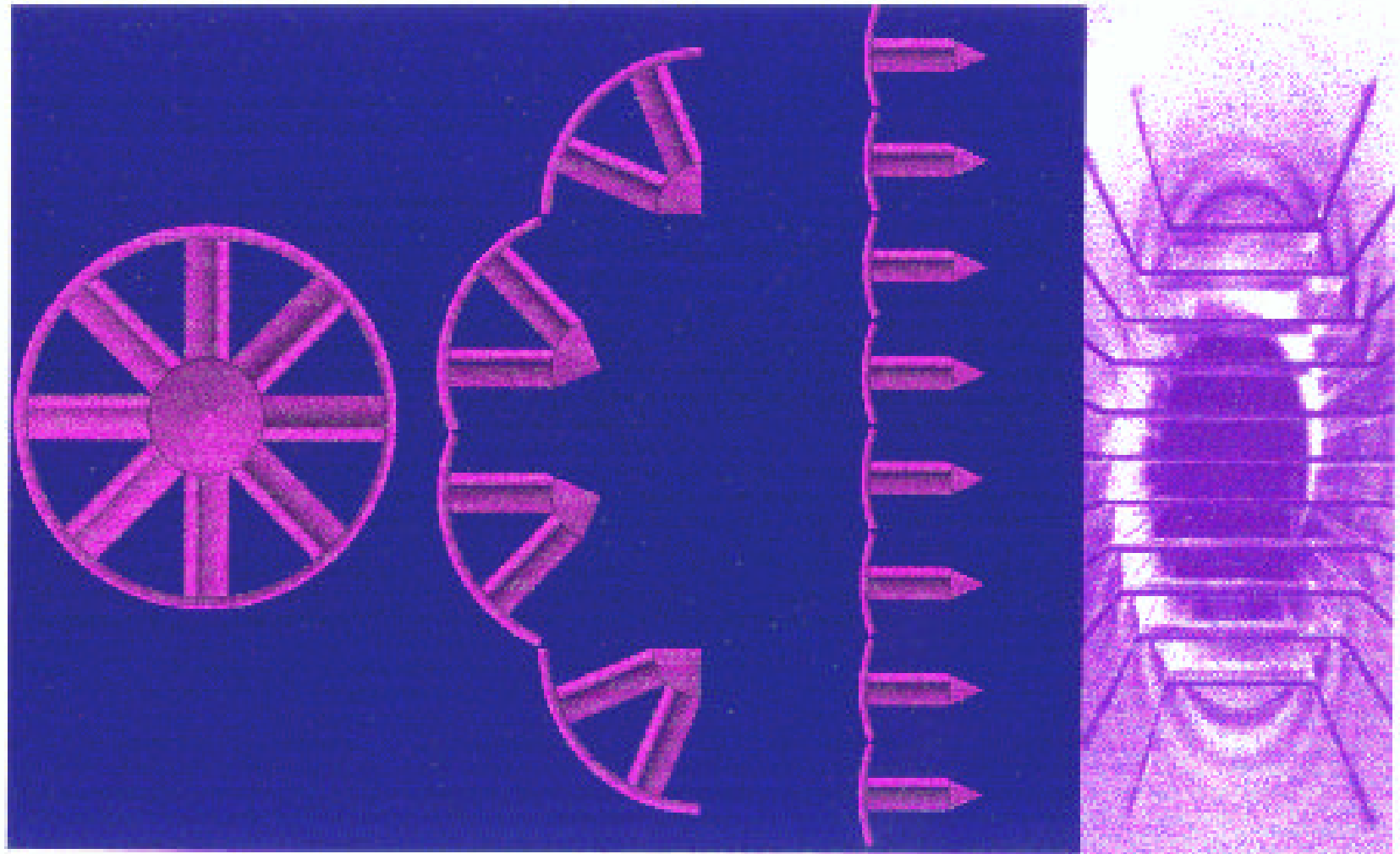
NO_x PREDICTED CFD 15%O₂



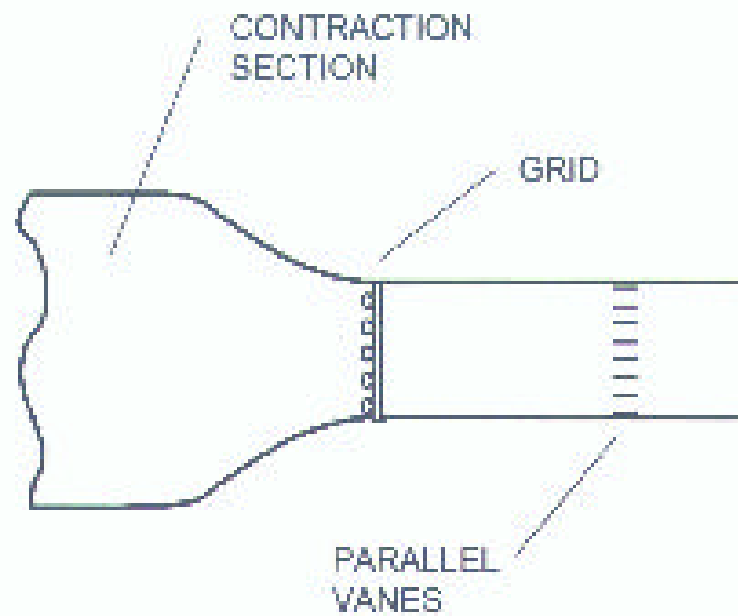
MEASURED EMISSIONS@15%O2



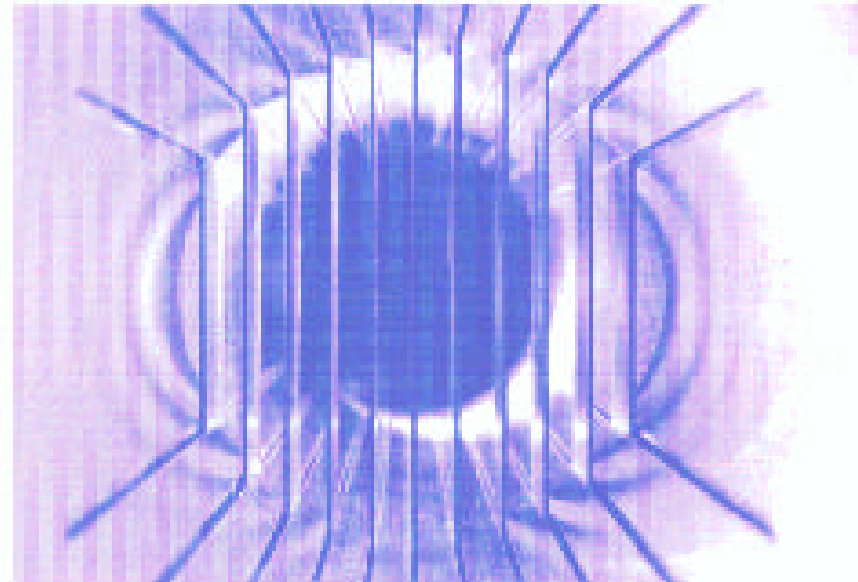
VANE CONCEPT



EXPERIMENTAL SETUP

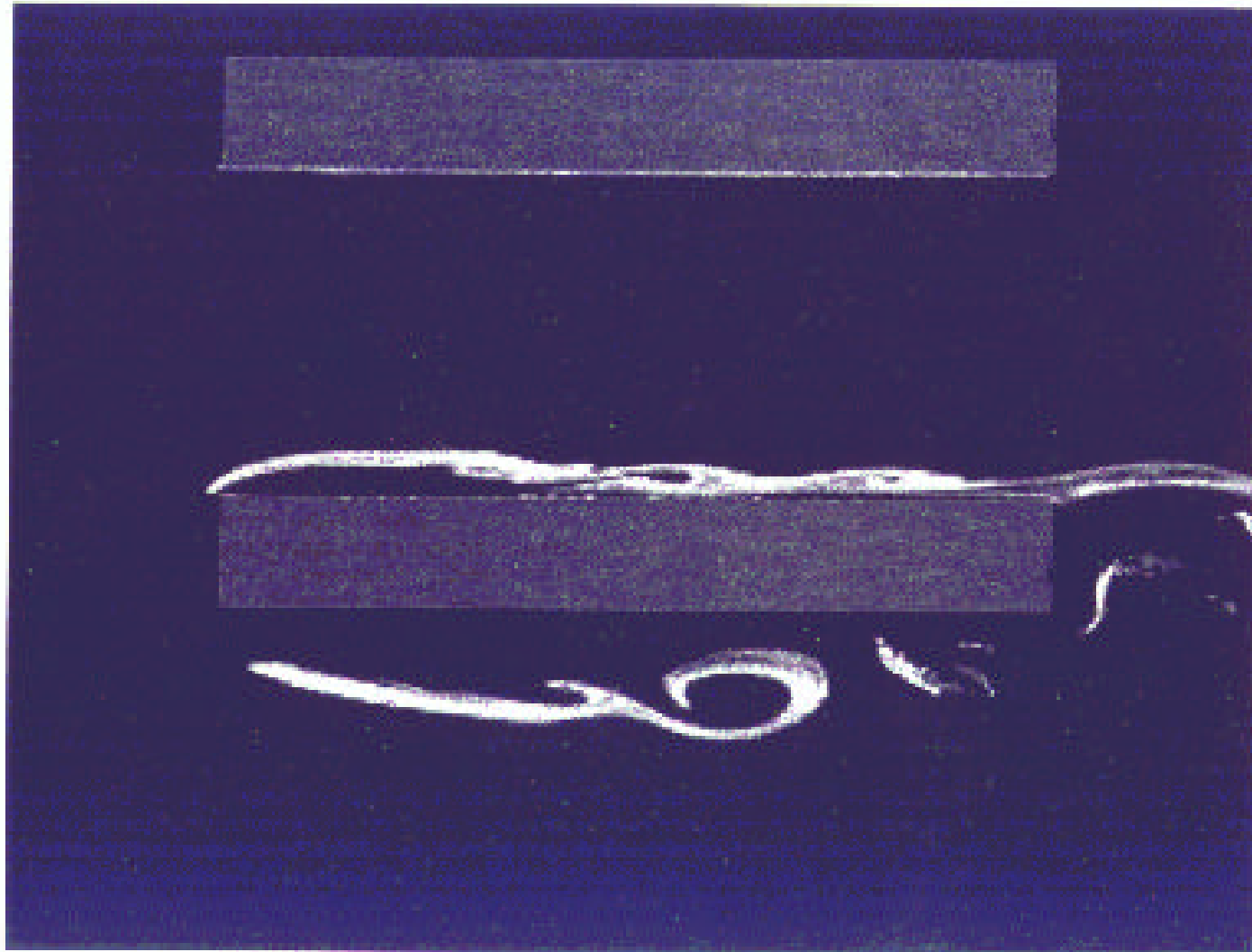


SCHEMATIC OF VANE
TEST FIXTURE



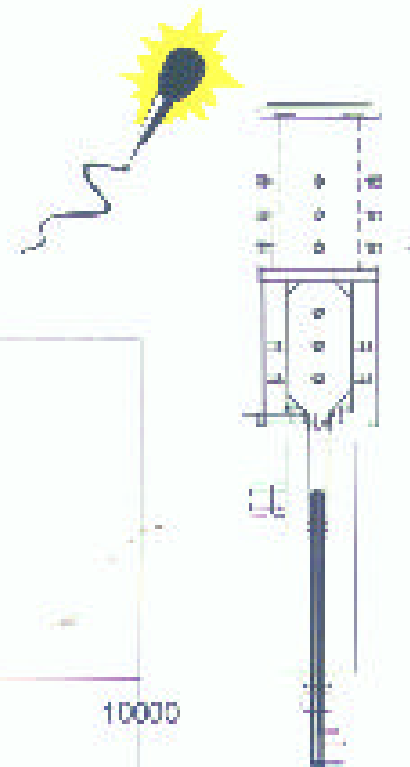
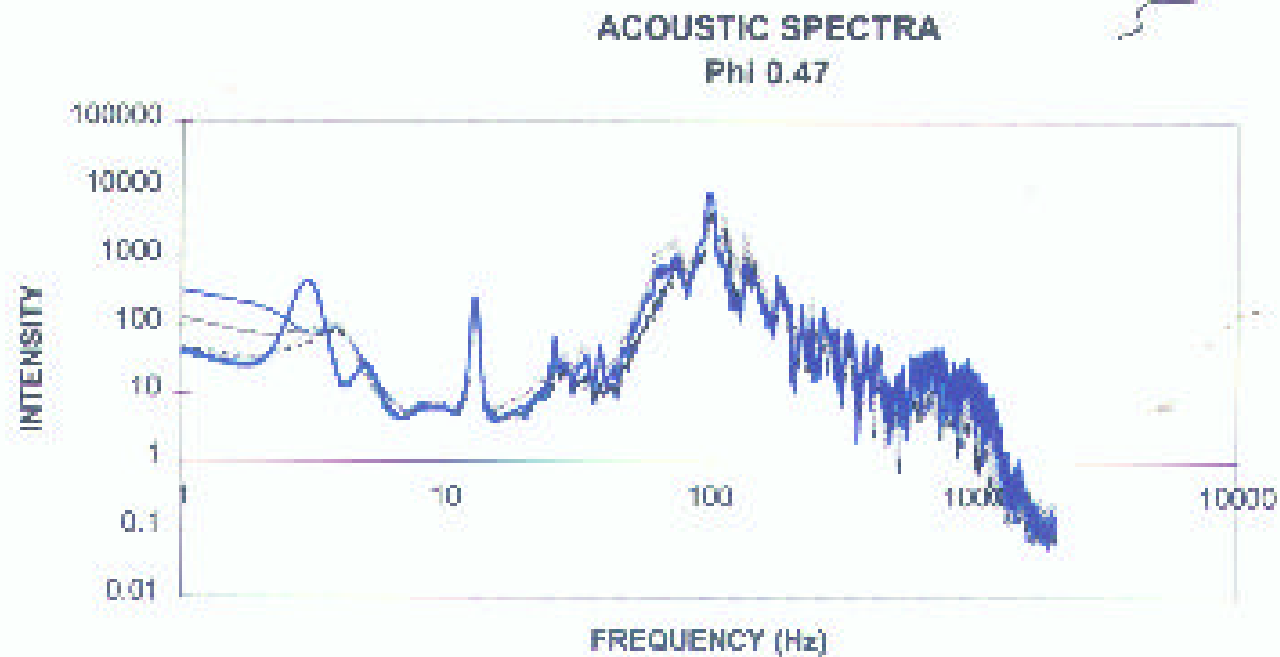
PHOTOGRAPH OF VANES

FLOW VISUALIZATION



ACOUSTIC SETUP

- MEASUREMENT OF STABILITY
- TEMPORAL BEHAVIOR OF COMBUSTOR
- 5 TO 5000 HZ
- SAMPLING RATE IS 10000 HZ



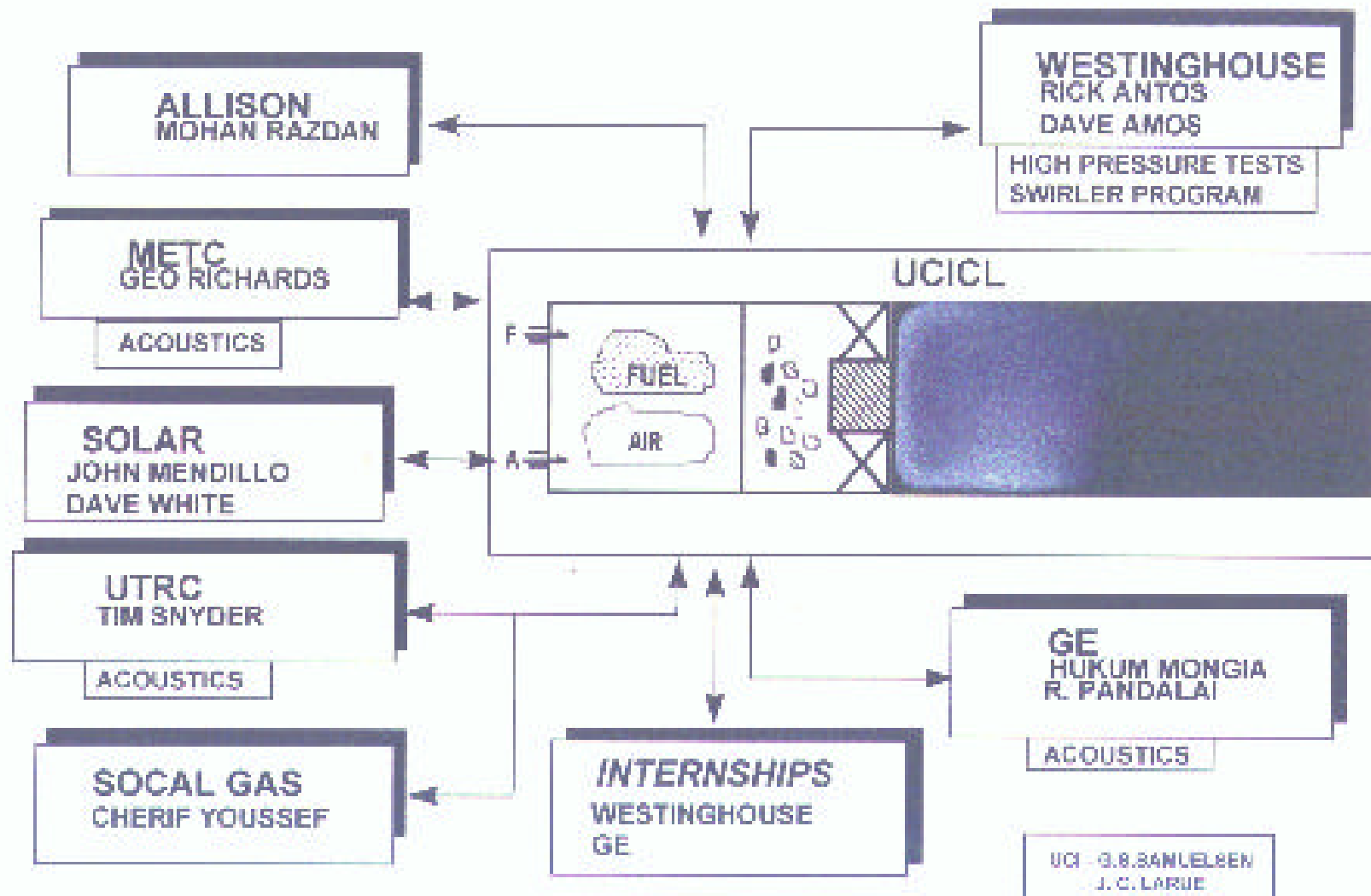
RESULTS

- DOE STUDY REVEALS THAT THE SIGNIFICANT PARAMETER IN NO_x PRODUCTION IS THE SPATIAL UNMIXEDNESS
- CO PRODUCTION IS RELATED TO VANE NUMBER
- MEASUREMENTS BEFORE AND AFTER THE SWIRLER SHOW VARIATION IN THE SPATIAL AND TEMPORAL UNMIXEDNESS
- UNMIXEDNESS IS RELATED TO COMBUSTOR PERFORMANCE
- CFD RESULTS REVEAL THAT WEIGHTING THE FUEL IN THE INNER REGIONS LEADS TO HIGH NO_x PRODUCTION
- COMBINING CFD AND EXPERIMENT PROVIDES FOR AN IMPROVED UNDERSTANDING OF COMBUSTOR BEHAVIOR

NEXT STEPS

- HIGH SPEED FLOW VISUALIZATION
- CONTINUED EVALUATION OF SPATIAL AND TEMPORAL UNMIXEDNESS
- DETAILED INVESTIGATION OF SELECT CASES: HIGH PERFORMANCE AND LOW PERFORMANCE
- CHARACTERIZATION OF AEROTHERMAL CHEMICAL FIELDS FOR SELECT CASES
- CFD STUDY OF SELECT CASES: INLET PROFILES FROM EXPERIMENT
- ACOUSTIC STUDY AND CORRELATION TO EMISSIONS
- UNMIXEDNESS STUDY AT ELEVATED PRESSURE AND TEMPERATURE

INDUSTRIAL COLLABORATION



INDUSTRIAL INTERNSHIPS



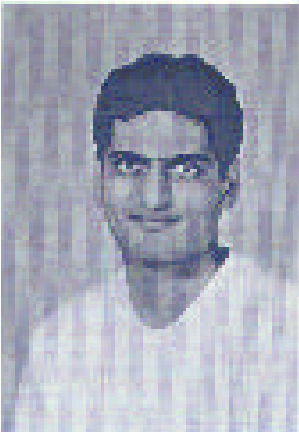
LEONEL ARELLANO
PRATT & WHITNEY



ARASH ATESHKADI
GE-CRD



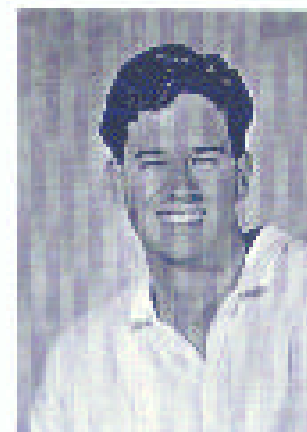
MAY LEONG
GE-AE



SURESH VILAYANUR
WESTINGHOUSE



OANH NYUGEN
ALLIED SIGNAL



NEIL DAVIS
SOLAR